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Optimizing construction progress by evolutionary algorithm considering multi-objective criteria

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Abstract: In the process of construction and installation, emergency requirements are designing a reasonable construction schedule. A suitable construction schedule will make an important contribution to reducing costs and saving construction time. Research on optimizing construction progress according to many goals to balance both time and resources is a difficult job, requiring a lot of effort. This study proposes the application of an evolutionary algorithm in optimizing the construction process with Gantt charts to meet the multi-target requirements. The multi-target function is built based on single target criteria and is used as the cost function of the evolutionary algorithm. Application results with specific projects show multi-target optimization by using evolutionary algorithms that allow automatically building a suitable and balanced construction schedule between targets. This study is expected to reduce project managers' work by providing an effective support tool.

Keywords: Construction schedule; Evolution Algorithm; Project Management.

1. Introduction

Designing a construction schedule is an important step in construction management. A properly designed construction schedule will contribute important value in reducing costs and saving construction time.

Currently, in the process of calculating and designing the construction schedule, engineers are often only interested in optimizing according to the project implementation time or the necessary resources of the project. That leads to the fact that when putting out actual construction, the project construction time is prolonged or resources such as manpower and machinery are short, leading to a delay in the progress of the work. The study of optimizing construction progress according to multiple objectives to balance both time and resource factors is a difficult job, requiring a lot of effort. The reason is that there is an inverse relationship between construction time and resources [1], [2]. A project that wants to speed up the schedule needs to increase resources sometimes beyond the ability of the contractor to supply, on the contrary, if the resources are low, the project will be delayed, leading to delays. In addition, when both resources and time are guaranteed as required, it is also necessary to consider the rationality of the resource chart, which is an important factor in assessing the reasonableness of the construction schedule.

The study of optimizing construction progress has been mentioned in documents and textbooks on construction organization [3]. However, new content only stops at the introductory level, suggesting that it is not detailed and often stops at the optimization of a single goal such as a specific time or resource. There is no specific research on multi-objective optimization problems in construction schedule design.

There have been many domestic and foreign studies on optimizing construction progress such as Hoang Nhat Duc (2015) [4] uses a differential evolution algorithm to optimize construction costs; Tran Duc Hoc (2019) [5] uses the multi-objective self-adjusting search symbiotic algorithm (AMOSOS) to solve the time-cost balance problem in projects with repetitive work. used in optimizing construction progress according to the network diagram; Hoang Thi Canh (2019) [6] used genetic algorithms to optimize the network diagram according to time and cost criteria; Zhang et al. (2015) [7] used seed swarm and differential evolution algorithms to optimize multi-resources for construction progress according to horizontal diagrams. Chassiakos and Sakellaropoulos (2005) [8] also uses a linear/integer programming model to provide a project time cost curve to optimize project time. El-Rayes and Kandil, 2005 [9] propose a quality objective function consisting of several measurable quality indicators for each activity, this can convert the multivariable objective function into a single variable, helping to optimize the multi-objectives.

The above studies have shown clear advantages of optimized plans and schedules over non-optimized plans and schedules. However, those studies mostly focused on optimizing for one goal like cost or time. They do not refer to multi-objectives such as optimizing the human resource graph or balancing the two sides of the balance between time and resources.

The above analysis shows that the optimization of construction organization design in the direction of multi-objectives is topical, scientific, practical, urgent, and feasible.

2. Research Methods

2.1. Gantt Chart (GC)

A Gantt chart is a type of horizontal bar chart that is commonly used in project management which was first presented by Henry Laurence Gantt in 1910 [10]. It provides a visual representation of the project schedule, with each task or activity represented as a bar that spans the duration of the task. The Gantt chart displays the start and end dates of each task, as well as their dependencies on other tasks. It also includes information about the resources assigned to each task, such as the people or equipment required to complete the task (**Fig 1**).

Gantt charts are useful tools for project managers because they provide a clear and easy-to-understand overview of the project schedule. They allow managers to track the progress of the project, identify potential delays or bottlenecks, and make adjustments to the schedule as needed.

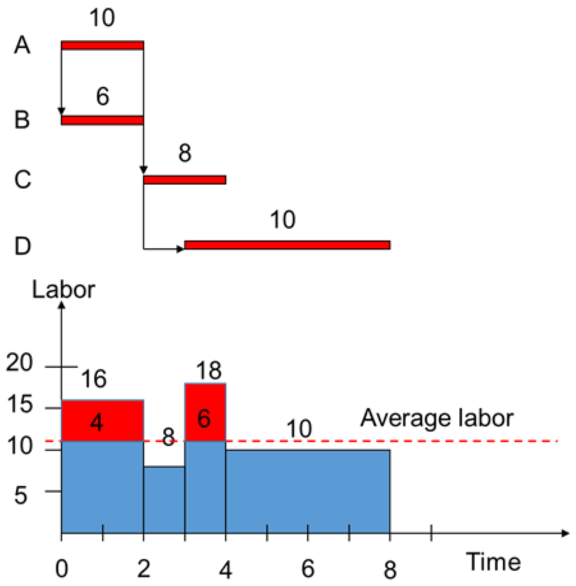

Fig 1. Typical Gantt chart

2.2. Evolution Algorithm

Evolutionary algorithms (EA) are a class of optimization algorithms that are inspired by the process of biological evolution. The goal of an EA is to find the optimal solution to a problem by iteratively generating and evaluating a population of candidate solutions, and then using selection, reproduction, and mutation operators to generate new solutions that are similar to the better solutions from the previous generation. The basic idea behind EAs is to model the process of natural selection, in which the fittest individuals are more likely to survive and reproduce, passing their advantageous traits on to the next generation. In an EA, candidate solutions are represented as chromosomes or genomes, and the fitness function evaluates how well each solution performs on the problem being solved. The selection operator chooses the best solutions from the current population to form the next generation, and the reproduction operator combines pairs of solutions to produce new solutions. The mutation is used to introduce genetic diversity into the population by randomly changing the values of some of the genes in the chromosomes. This allows the search to explore new regions of the solution space, potentially leading to better solutions. The process of selection, reproduction, and mutation is repeated over many generations, with the hope that the population will converge to a near-optimal solution.

EAs have been successfully applied to a wide range of optimization problems in many fields, including engineering, computer science, economics, and biology [11], [12]. They are particularly useful in cases where the search space is large or complex, and where traditional optimization methods may struggle to find the global optimum.

2.3. Gantt Chart optimization model using Evolution Algorithm

First, the schedule of a task in the construction project is determined by the starting point, the work execution time (T), and the ending time. In addition, the task schedule can only be located in terms of the execution time parameter and its relationship with other tasks in the project (**Fig 2**).

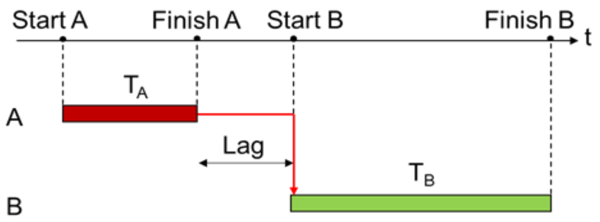

Fig 2. Parameters of a typical task

In addition, parameters related to task resources such as workers are defined as follows equations:

Where the task mainly uses the manual resource, the resource needs of i^{th} task is determined as follows:

$$M_i = V_i . q_i \quad (1)$$

Where V_i is the volume of the task; q_i is the construction norm of the task, which is related to the basic construction norms of the Ministry of Construction [13].

Then, the time to perform the i^{th} task is determined by the formula:

$$T_i = \frac{M_i}{N_i} \quad (2)$$

Where N_i is the number of workers used to complete the task i^{th}.

In the case of using mechanization ability, the time to complete the i^{th} task is calculated according to the following formula:

$$T_i = \frac{M_i}{m_i . n_i} \quad (3)$$

In which m_i is the number of construction machines and n_i is the number of machine shifts in one day.

In this study, to ensure the unity between the tasks, the two most important parameters of the task are put into the optimal research for the project: the Time of work (T) and the Lag time (L) between the tasks. The remaining parameters such as the number of workers (N) are calculated through the resource parameter (M) and work time (T).

It is said that, if a project has j task, the amount of variable that needs to be optimized is 2j. And the structure of a typical chromosome in EA is shown in **Fig 3**.

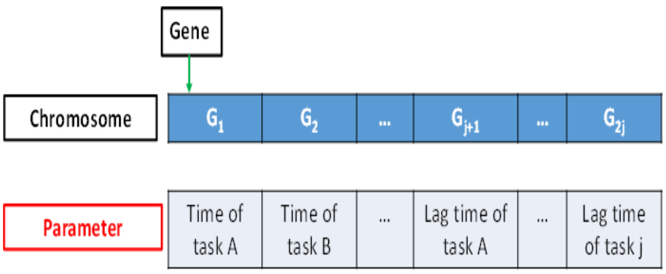

Fig 3. Structure of chromosomes and genes in EA

The process of optimizing the construction progress according to the evolution algorithm is carried out as follows:

Step 1. Create a random population consisting of an individual p, in which, gene values are randomly taken within their permissions.

Step 2. Randomly select parents, and let them interfere with each other to create the next generation (**Fig 4**).

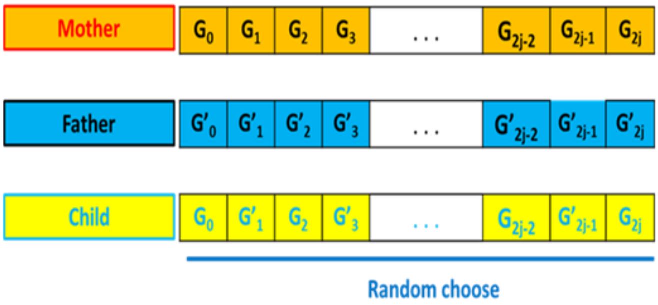

Fig 4. The mating process of the individuals in EA

Step 3. Allow some individuals in the mutant younger generation. Mutations are the process of replacing some random genes in the chromosome chain, giving evolution the opportunity to find better genes.

Step 4. Eliminate weak individuals to ensure the number of individuals in the population is constant.

Repeat from step 2 to 4 to make sure the convergence or the number of generations as required.

Because the optimization algorithm includes boundary conditions and constraints, the following improvements should be noted:

The mating and mutation processes ensure that only new individuals that satisfy the constraints are produced. With boundary conditions, this is easily solved by initializing individuals with genes that are within the allowable range, while the mutation process also selects only the allowed genes. However, with constraints, this is more complicated. Specifically, if new individuals are born or mutated that do not satisfy the constraint, they will be immediately removed and the replacement process will be repeated until the instance meets the correct constraint condition. At that time, new individuals will be eligible to be added to the population. The above improvement will be shown in **Fig 5**.

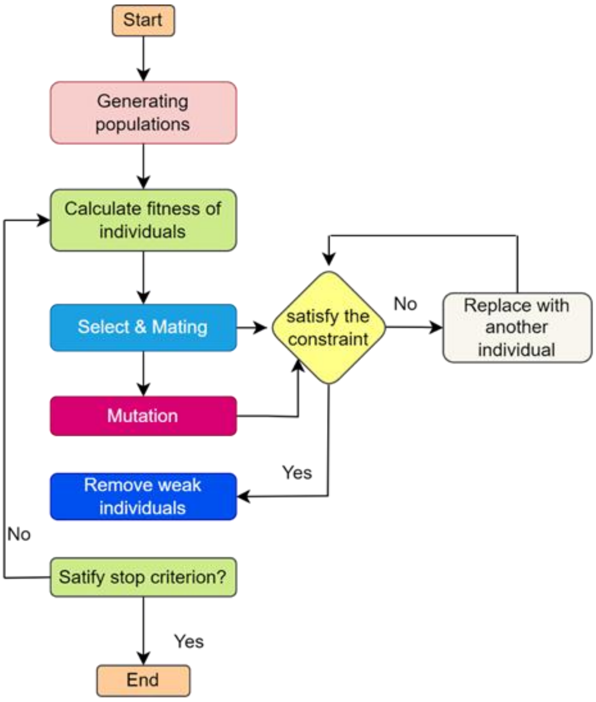

Fig 5. Flowchart of EA used in this study

2.4. Evaluation Criteria of the construction progress

In this study, the criteria for assessing the rationality of the construction progress include construction time, maximum worker resources, and suitable resource charts. The Time criteria are determined as follows:

$$\begin{cases} T \rightarrow \min \\ T \leq T_{max} \end{cases} \quad (4)$$

Where T is to total construction time of the project; T_{max} is the allowable time limit.

The resource limit is calculated as follows:

$$\begin{cases} N \rightarrow \min \\ N \leq N_{max} \end{cases} \quad (5)$$

Where N is the largest labor of the day, N_{MAX} is the permitted labor limit.

The appropriate resource chart is assessed by 2 coefficients K1 and K2 as follows:

$$\begin{cases} K_1 \rightarrow 1 \\ K_1 = \dfrac{N}{N_a} \end{cases} \quad (6)$$

Where N_a is the average number of workers during the construction period.

$$\begin{cases} K_2 \to 0 \\ K_2 = \sum_{i=1, N_i > N_a}^{T} \frac{N_i - N_a}{N_i} \end{cases} \quad (7)$$

Where N_i is the number of workers in i^{th} day in the construction period.

It can be seen that, while the K_1 coefficient is characterized by the correlation between the largest number of workers and the average number of workers, the K_2 coefficient tends to control the number of workers not exceeding the average level.

It is important to note the contradiction between T and N. Once it is necessary for T to decrease, it is needed to increase N. Therefore, two criteria T and N will not reach the same optimal at the same time. To solve that problem, the 4^{th} criterion has been built, representing the optimal criteria of multi variables. That criterion is defined as follows:

$$D = a_1 \frac{T}{T_{max}} + a_2 \frac{N}{N_{max}} + a_3 \left(\frac{K_1}{2} + K_2 \right) \quad (8)$$

where, the coefficients a_1, a_2, a_3 were selected according to the specific priority requirements of the construction progress and make sure $a_1 + a_2 + a_3 = 1$.

3. Results and Discussions

Table 1. Key-parameters range of the construction process schedule

Parameter	Range
Number of days per task	1÷20
Number of shifts per machine per day	1÷3
Max total construction days allowed	250

Table 2. Case studies of construction schedule

Case	Criteria	Constraint
1	Total construction time (T) → min	T ≤ 250
2	Number of worker (N) → min	T ≤ 250
3	Multi-object criteria (D) → min	T ≤ 250

Table 3. Initialize parameters of the EA

Parameter	Value
Population	100
Mating rate	50%
Mutation rate	7.5%
Generation	Covergence reach to 0.001

3.1. Describe the illustration project

Construction works for the underground part and two floors, constructed in Hanoi. The project construction schedule includes 48 tasks, which have been arranged in the order of construction. All the task's volume has been disassembled, and the cost of labor and machine is estimated and illustrated in **Appendix A**. The key-parameters range of construction schedule are showed in the **Table 1**. The boundary of all variables are shown in **Appendix A** and the constraint is shown in the **Table 2**.

It's important to note that in this construction schedule, the task relationship is in the Finish-Start or Start-Finish form. These relationships are declared and fixed before the optimization is performed. This will partially limit the optimal result because the relationship between the jobs in progress is also a factor that should be included in the optimization.

Construction progress according to Gantt chart made in Excel with full working relationships according to the construction process. The evolution algorithm is conducted based on the VBA platform, directly interacting with Excel. The allowable value ranges of the two parameters Time and Lag are also preselected and given in Appendix A.

3.2. Optimizing construction progress

First, a random construction schedule is generated. This schedule is built according to the construction process and repeated several times until the total construction days are within the allowable range. The resource chart of the initiate schedule is shown in **Fig6a**. It can be seen that the construction schedule plan is randomly generated after several iterations, giving quite good results.

Specifically, this process took 227 days to complete with the highest number of laborers at 224. However, it can also be seen that the resource chart of the initial construction schedule is not qualitatively and quantitatively reasonable, when the construction distance is not continuous, there are many gaps and the total number of construction days is still to be shortened further.

Then, to build a reasonable construction schedule, the EA-Gantt model is implemented to optimize the construction schedule.

The Initialization parameters of the EA model are shown in **Table 3** and remained unchanged throughout the study.

In this study, a total of 3 case studies were built according to different optimization criteria (**Table 2**).

It is important to note: In case 3, the coefficients were selected as follows: $a_1 = 0.7$; $a_2 = 0.2$ and $a_3 = 0.1$. These coefficients are chosen according to the subjectivity of the study when the optimal coefficient in terms of time is wanted to be higher than the remaining coefficients.

The results of the optimization process are illustrated in **Fig 6 b,c,d** and **Table 4**.

Table 4. Compare results

Criteria	T	N	K_1	K_2	D
Unit	(days)	(workers)	-	-	-
Initial	227	224	5.47	0.51	1.26
1	46	2153	6.11	0.48	3.35
2	206	122	2.73	0.37	0.91
3	98	138	1.41	0.17	0.55
Improve (%)	56.83	38.39	74.29	67.56	56.69

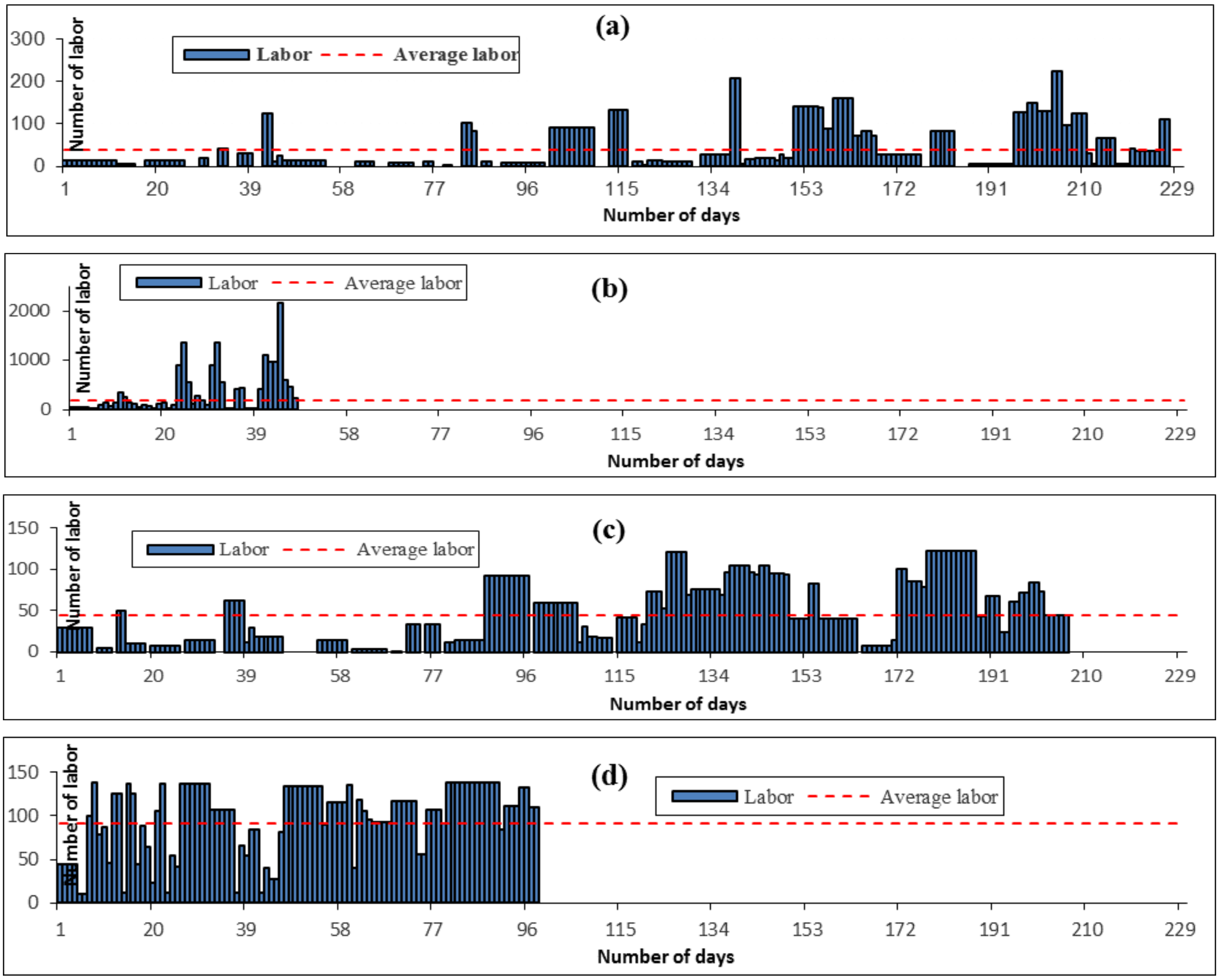

Fig 6. Visualize the resource graph for : (a) - Initial construction schedule case; (b) - Case study 1 ; (c) - Case study 2 ; (d) - Case study 3

The results show that all three study cases 1, 2, and 3 give a better construction schedule than the initial case. Specifically, in terms of construction time criteria, case study 1 gives the shortest construction time (46 days), saving 181 days (79%) compared to the initial progress. However, the resources used in case study 1 are too large, specifically, the maximum number of laborers is up to 2153 on the 43rd construction day.

In another development, case study 2 is more concerned with limiting the maximum number of laborers while still ensuring the total construction time $T \leq Tmax$. The result seems to be much better, when the maximum laborers only reach 122 while the coefficient K_1, K_2 is much more reasonable than in case study 1. However, the construction time T still reached 206 days, not much decrease compared to T_{max} (250 days).

In the last survey case, using multi-objective optimization through criterion (D), the results seem to achieve the most optimal and balanced level. Specifically, this schedule only took 98 days to complete with the highest number of workers at 138. The cost savings in time was 56.83% and in labor was 38.29% compared to the initial scheduled. At the same time, the coefficients K_1 and K_2 both reached the best value in all the case studies. The optimal construction progress and accompanying parameters are shown in **Appendix B**.

4. Conclusion

In this study, the construction schedule plan by the Gantt chart was proposed to be optimized based on the evolutionary algorithm.

The single evaluation criteria of time and labor resources are used as the optimization criteria. In addition, a multi-objective evaluation criterion is also proposed to help find the best construction schedule.

The research results show that the use of EA is suitable to optimize the construction plan on the Gantt chart. The use of multi-objective evaluation criteria as the cost function gives more impressive results than single-objective criteria. Specifically, the schedule saved 56.83% of the total construction time, and 38.39% of max labor, and satisfied the criteria for evaluating the reasonableness of the labor chart.

One limitation of the study is that it has not yet considered the diversity constraints between tasks in a project. This can continue to be implemented in the next studies to further optimize the construction schedule.

The study is valuable for project managers and construction managers by providing a powerful tool for construction schedule planning.

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Appendix A. List of construction tasks and permission of variables

No	Task name	Boundary of Duration	Unit	Predecessor	Boundary of Lag time	Volume	Norm
1	Pile construction	(4;12)	100m	0	(0;3)	5	2.3
2	Excavation by machine	(2;4)	100m3	1	(0;3)	12.49	0.316
3	Excavation by laborer	(1;10)	m3	2	(0;3)	200	0.5
4	Break the pile head	(1;10)	m3	3	(0;3)	7.533	5.1
5	Pouring concrete lining the foundation	(1;10)	m3	4	(0;3)	28.6	1.42
6	Construction of reinforcing steel foundation	(1;10)	T	5	(0;3)	11.07	8.34
7	Construction of foundation formwork	(1;10)	100m2	6	(0;3)	6.51	38.28
8	Concrete pump foundation, bracing	(1;1)	m3	7	(0;3)	114.48	0.0035
9	Remove foundation formwork	(1;10)	100m2	8	(0;3)	6.51	19.14
10	Backfill the first phase by machine	(1;10)	100m3	9	(0;3)	4.49	0.094
11	Install column neck formwork	(1;10)	100m2	10	(0;3)	1.17	38.28
12	Pouring concrete neck columns	(1;10)	m3	11	(0;3)	9.558	4.5
13	Remove column neck formwork	(1;10)	100m2	12	(0;3)	1.17	19.14
14	Backfill the second phase by machine	(1;2)	100m3	13	(0;3)	17.68	0.094
15	Installation of column reinforcement on the 1st floor	(1;10)	T	14	(0;3)	12.19	8.48
16	Installation of column formwork on the 1st floor	(1;10)	100m2	15	(0;3)	4.37	38.28
17	Pouring concrete columns	(1;1)	m3	16	(0;3)	39.51	0.0035
18	Remove column formwork on the 1st floor	(1;10)	100m2	17	(0;3)	4.37	19.14
19	Installation of floor beams formwork on the 1st floor	(1;20)	100m2	18	(0;3)	25.42	32.42
20	Installation of floor beams reinforcement on the 1st floor	(1;20)	T	19	(0;3)	42.92	12.42
21	Pouring concrete floor beams	(1;1)	m3	20	(0;3)	250	0.0035
22	Concrete curing	(2;5)	Labor	21	(0;3)		
23	Remove floor beams formwork on the 1st floor	(1;10)	100m2	22	(7;14)	25.42	16.21
24	Build the wall on the 1st floor	(1;10)	m3	23	(0;3)	15.56	2.7
25	Construction of stairs	(1;10)	m3	24	(0;3)	4.16	7.99

No	Task name	Boundary of Duration	Unit	Predecessor	Boundary of Lag time	Volume	Norm
26	Plastering the ceiling	(1;10)	m2	25	(0;3)	1296	0.5
27	Interior plastering	(1;10)	m2	26	(0;3)	1108.8	0.22
28	Install floor tiles	(1;10)	m2	43	(0;3)	1296	0.17
29	Install aluminum frame doors	(1;10)	m2	24	(0;3)	150	0.3
30	Installation of column reinforcement on the 2nd floor	(1;10)	T	21	(0;3)	12.19	8.48
31	Installation of column formwork on the 2nd floor	(1;10)	100m2	30	(0;3)	4.37	38.28
32	Pouring concrete columns	(1;1)	m3	31	(0;3)	39.51	0.0035
33	Remove column formwork on the 2nd floor	(1;10)	100m2	32	(0;3)	4.37	19.14
34	Installation of floor beams formwork on the 2nd floor	(1;20)	100m2	33	(0;3)	25.42	32.42
35	Installation of floor beams reinforcement on the 2nd floor	(1;10)	T	34	(0;3)	42.92	12.42
36	Pouring concrete floor beams	(1;1)	m3	35	(0;3)	250	0.0035
37	Concrete curing	(2;5)	Labor	36	(0;3)		
38	Remove floor beams formwork on the 2nd floor	(1;20)	100m2	36	(7;14)	25.42	16.21
39	Build the wall on the 2nd floor	(1;10)	m3	38	(0;3)	15.56	2.7
40	Construction of stairs	(1;10)	m3	39	(0;3)	4.16	7.99
41	Plastering the ceiling	(1;20)	m2	40	(0;3)	1296	0.5
42	Interior plastering	(1;10)	m2	41	(0;3)	1108.8	0.22
43	Install floor tiles	(1;10)	m2	42	(0;3)	1296	0.17
44	Install aluminum frame doors	(1;10)	m2	39	(0;3)	150	0.3
45	Exterior plastering	(1;20)	m2	39	(0;3)	1300	0.97
46	Exterior paint	(1;10)	m2	45	(0;3)	1300	0.091
47	Install electricity and water	(1;10)	m2	46	(0;3)	500	0.091
48	End	0		47	0		

Appendix B. Optimal construction schedule

ID	Name	Duration	Lag time	Resource Names
1	Pile construction	4 days	0	NC[45]
2	Excavation by machine	2 days	0	NC[10]
3	Excavation by laborer	1 day	0	NC[100
4	Break the pile head	1 day	0	NC[38]
5	Pouring concrete lining the foundation	1 day	0	NC[41]
6	Construction of reinforcing steel foundation	2 days	0	NC[46]
7	Construction of foundation formwork	2 days	0	NC[125
8	Concrete pump foundation, bracing	1 day	0	NC[12]
9	Remove foundation formwor	1 day	0	NC[125
10	Backfill the first phase by machine	1 day	0	NC[2]
11	Install column neck formwor	1 day	0	NC[45]
12	Pouring concrete neck columns	1 day	0	NC[43]
13	Remove column neck formwork	1 day	0	NC[22]
14	Backfill the second phase by machine	1 day	0	NC[2]
15	Installation of column reinforcement on the 1st	1 day	0	NC[103
16	Installation of column formwork on the 1st floor	5 days	0	NC[33]
17	Pouring concrete columns	1 day	0	NC[12]
18	Remove column formwork on the 1st floor	2 days	0	NC[42]
19	Installation of floor beams formwork on the 1st floor	6 days	0	NC[137
20	Installation of floor beams reinforcement on the 1st	5 days	0	NC[107
21	Pouring concrete floor beam	1 day	0	NC[12]
22	Concrete curing	2 days	0	NC[2]
23	Remove floor beams formwork on the 1st floor	8 days	7	NC[52]
24	Build the wall on the 1st floo	5 days	0	NC[8]
25	Construction of stairs	2 days	0	NC[17]
26	Plastering the ceiling	7 days	0	NC[93]
27	Interior plastering	7 days	0	NC[35]
28	Install floor tiles	2 days	0	NC[110
29	Install aluminum frame door	4 days	0	NC[11]
30	Installation of column reinforcement on the 2nd	2 days	0	NC[52]
31	Installation of column formwork on the 2nd floor	2 days	0	NC[84]
32	Pouring concrete columns	1 day	0	NC[12]
33	Remove column formwork on the 2nd floor	3 days	0	NC[28]
34	Installation of floor beams formwork on the 2nd floor	10 days	0	NC[82]
35	Installation of floor beams reinforcement on the 2nd	5 days	0	NC[107
36	Pouring concrete floor beam	1 day	0	NC[12]
37	Concrete curing	3 days	0	NC[2]
38	Remove floor beams formwork on the 2nd floor	5 days	7	NC[82]
39	Build the wall on the 2nd floor	2 days	0	NC[21]
40	Construction of stairs	4 days	0	NC[8]
41	Plastering the ceiling	12 days	0	NC[54]
42	Interior plastering	3 days	0	NC[81]
43	Install floor tiles	2 days	0	NC[110
44	Install aluminum frame door	3 days	0	NC[15]
45	Exterior plastering	15 days	0	NC[84]
46	Exterior paint	4 days	0	NC[30]
47	Install electricity and water	2 days	0	NC[23]
48	End	0 days	0	NC[0]